Methodology for Developing Photonic Architectures

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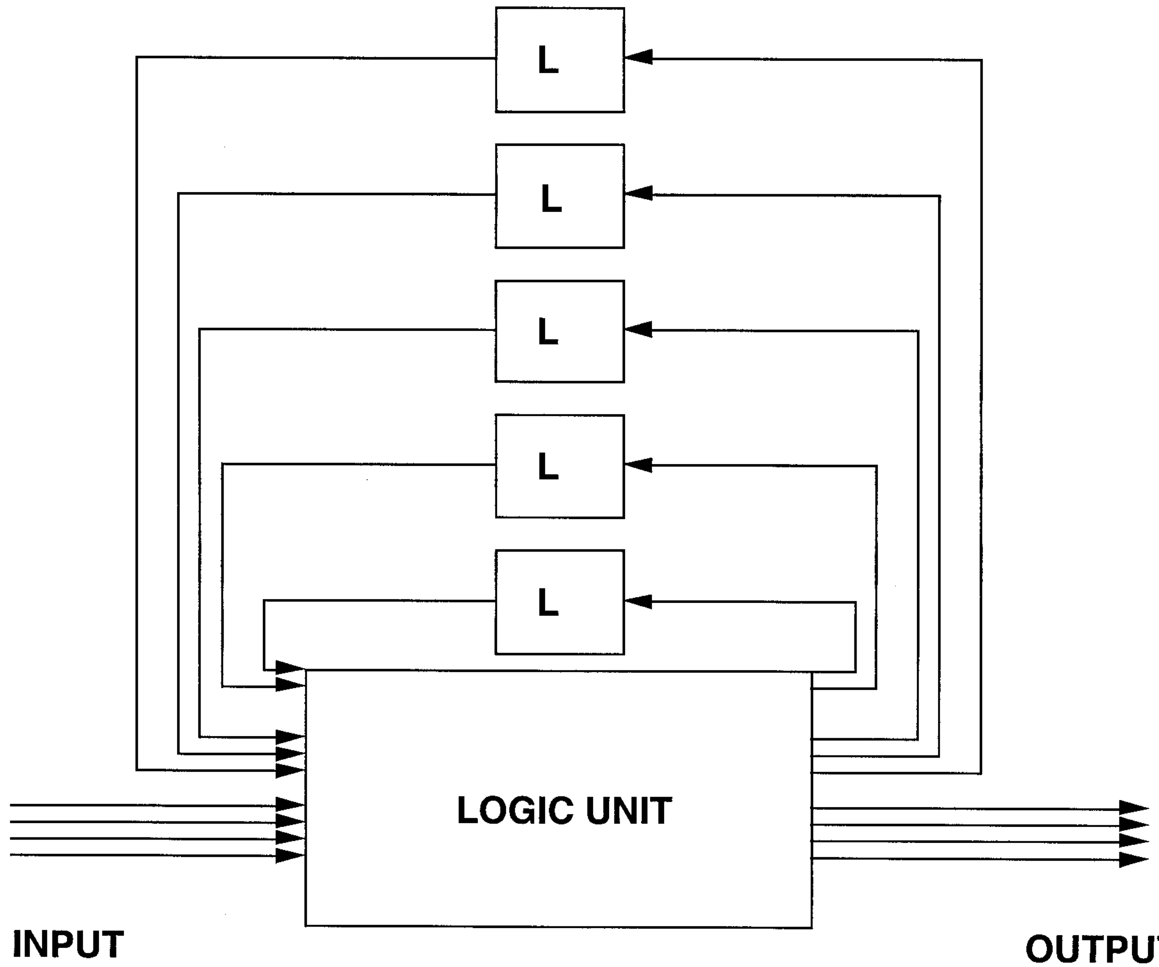
Section 367

OUTLINE

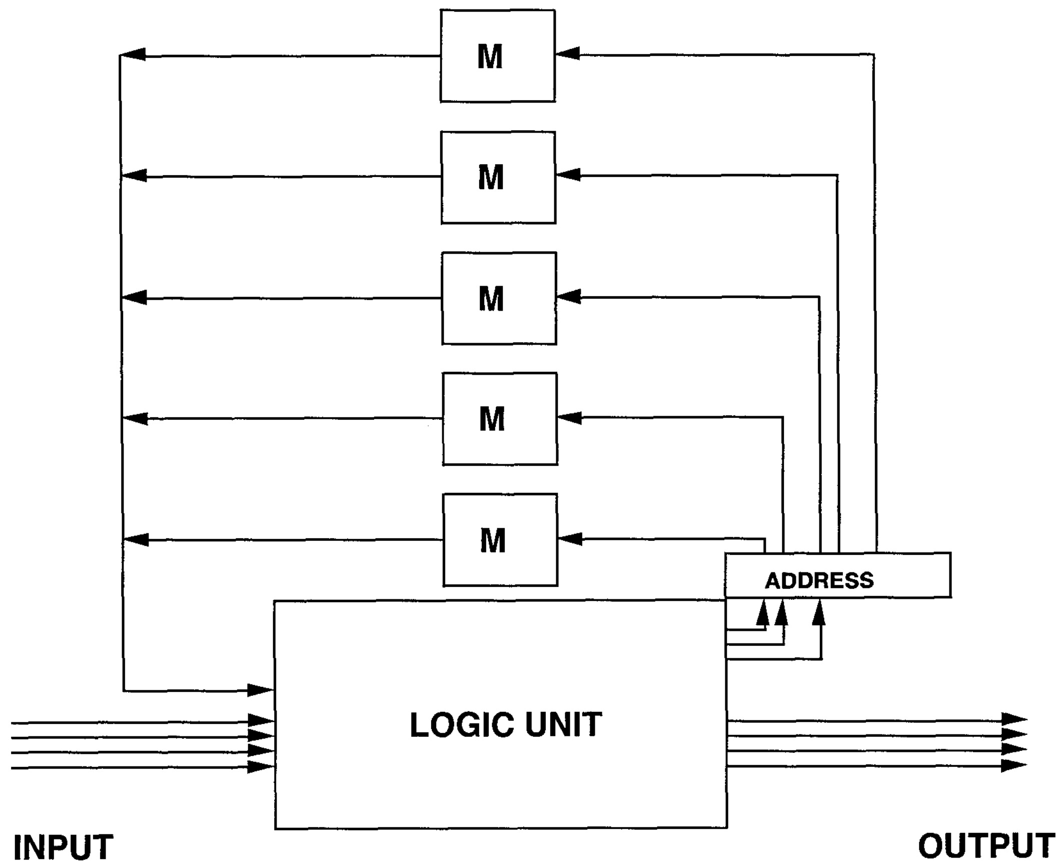
- Processor Background
  - Finite State Machine
  - Von Neumann Architecture
- System Implications of Physical Properties
- Multi-Level processors
- Optical processors
- DiVincenzo's requirements for Quantum computers

FINITE STATE MACHINE



FINITE STATE MACHINE

VON NEUMANN MACHINE



MODIFIED FINITE STATE MACHINE

Key Realizations Which We Take for Granted

- **Importance of digital regeneration**
  - Transition from analog to digital after proof that a bit could be regenerated nearly an infinite number of times without loss of information.*
- **Importance of timing control**
  - The ability to control the timing of information introduction into the processing loop *(i.e. Buffered storage and long term memory devices)*

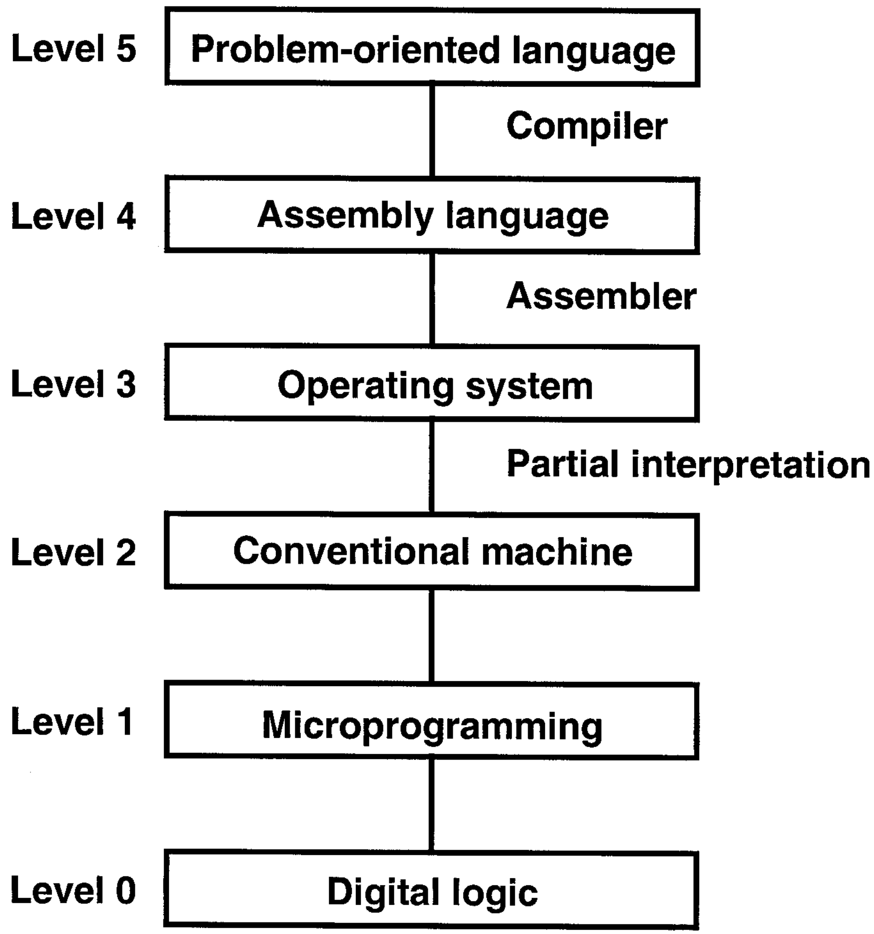
* J.H. Wilkinson, "Rounding Errors in algebraic Processes" (Prentice hall, Englewood Cliffs, N.J. 1963) Chapt. 1, pp 1-33.

System Implications of Physical Properties

- **Fermions - intrinsically serial architectures**
  - Radiative crosstalk limits interconnection packing density
  - Low active device switching powers
  - Low cost due from mature technology

- **Bosons - intrinsically parallel architectures**
  - Optical crosstalk is minimal up to point of detection
    - » High interconnect packing density
    - » Wavelength division multiplexing possible
  - Switching based on 2nd and 3rd order effects => need high optical intensity
  - Relatively higher cost except for passive classical optics components

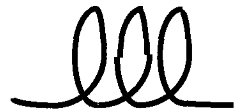
Digital Electronic Multi Level Machine

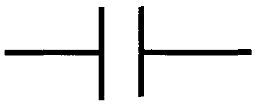


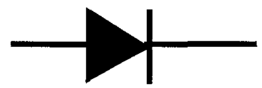
Physical Electronic Building Blocks

Physical devices:

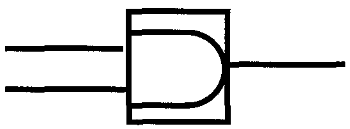

resistor

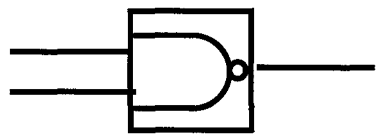

inductor

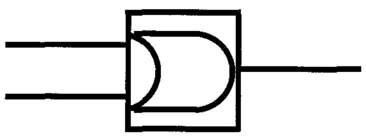

capacitor


diode

Basic Logic Functions


AND


NAND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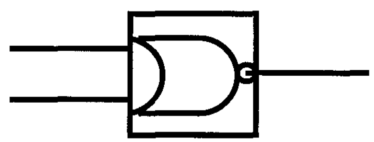
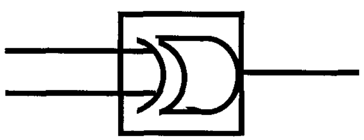
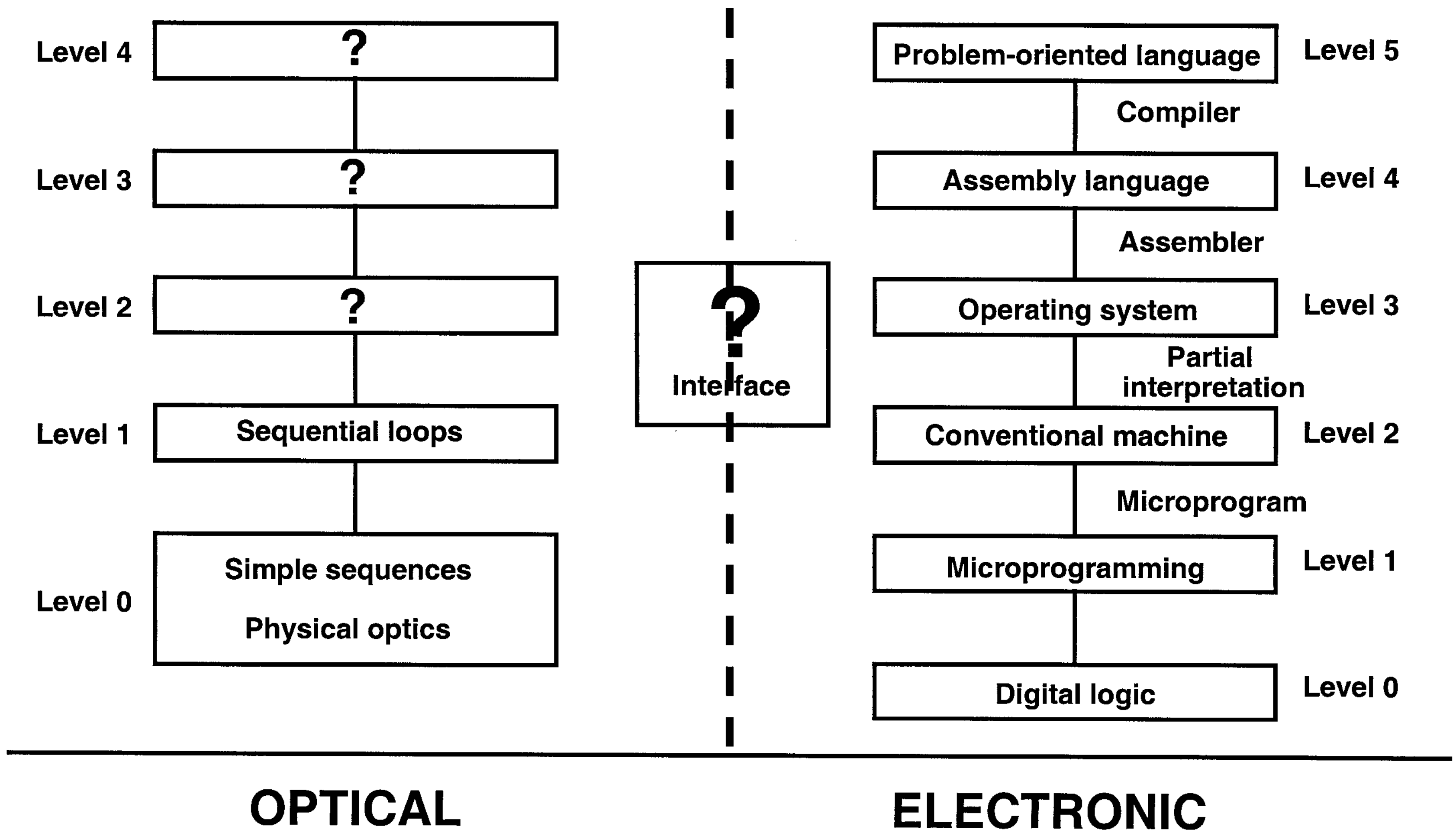

NOR


XOR

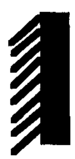
O-E INTERFACE



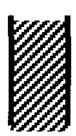
Physical Optical Building Blocks

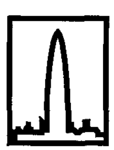
Passive Devices


lens

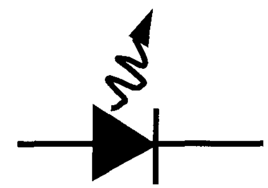

mirror


prism


etalon


notch filter

Active Devices


laser diode

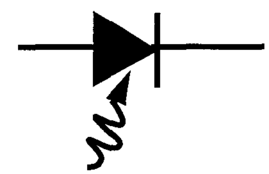
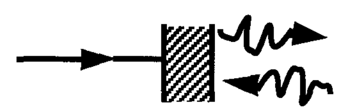
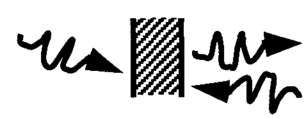
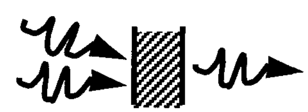


photo diode


e-beam SLM

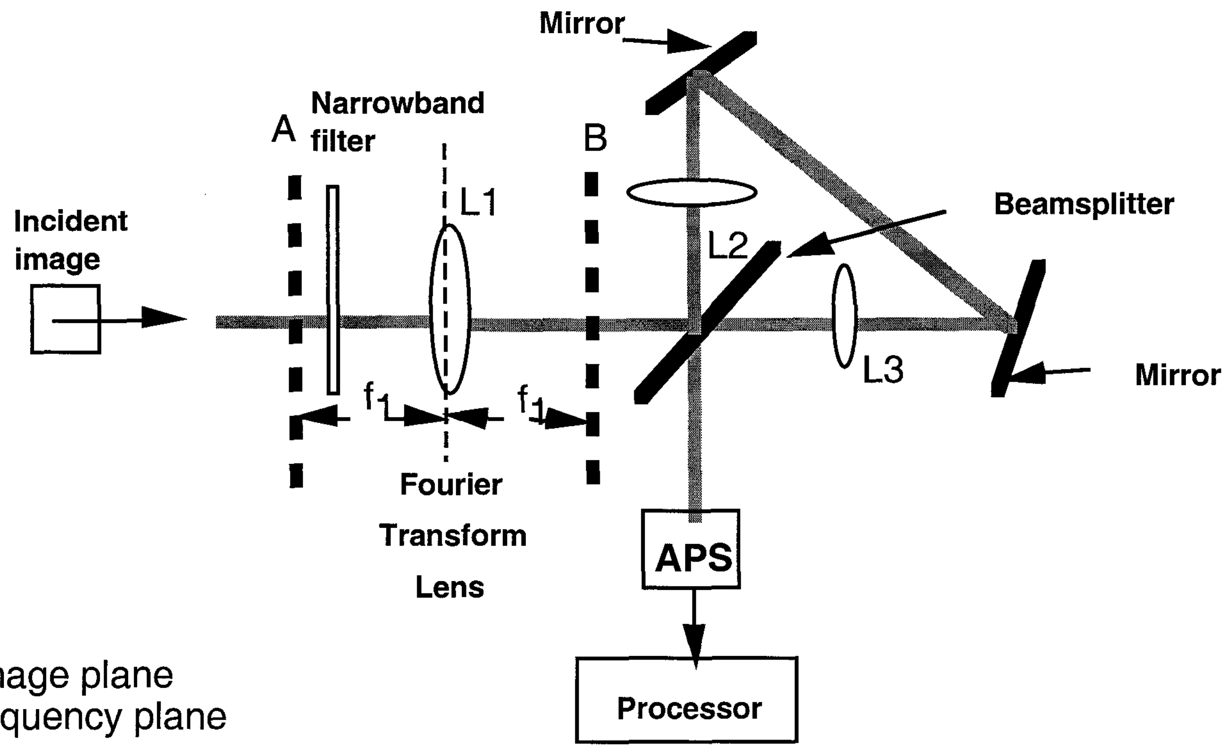

reflection SLM


OLE

MOSTLY ANALOG

Optical Schematics Rarely Expressed Functionally in a Systems Context

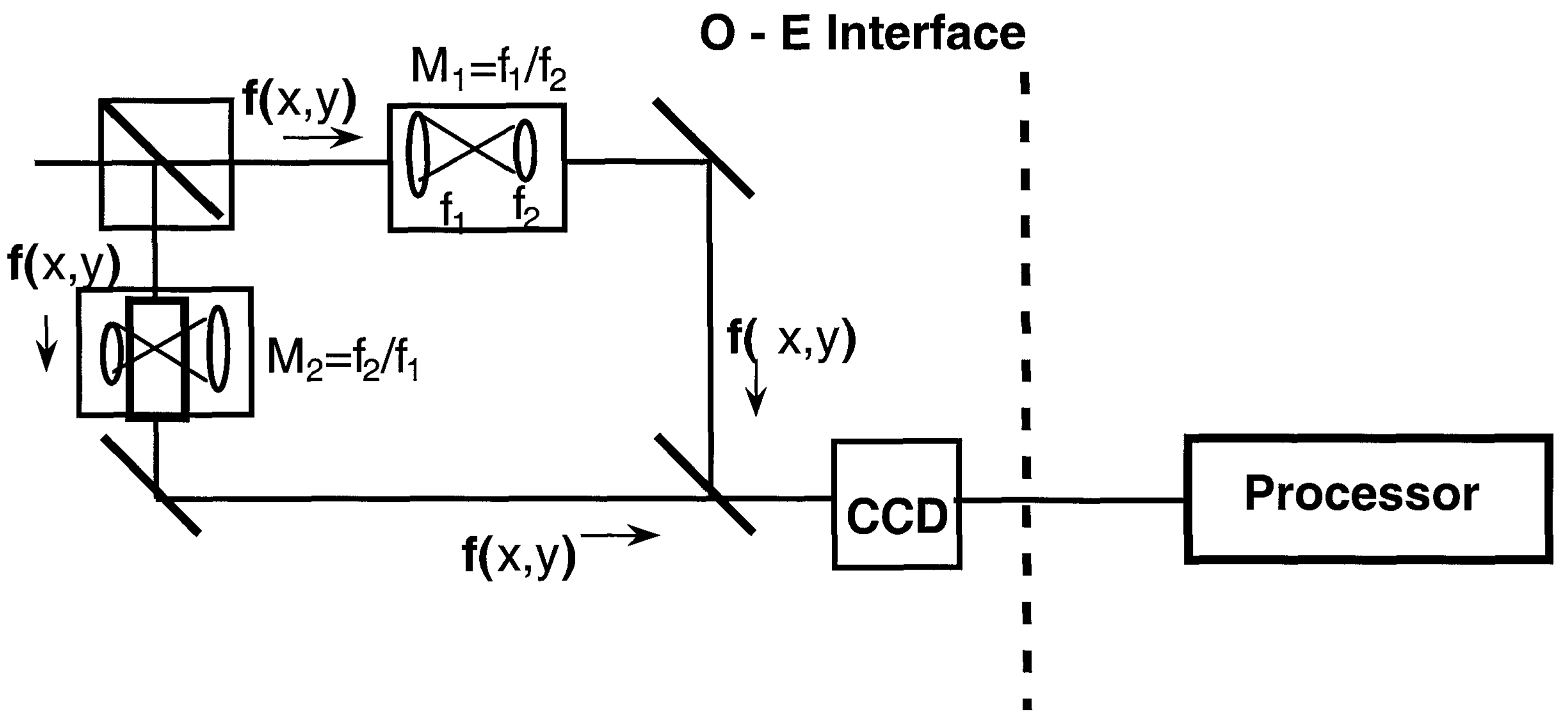
White Light holography



A = image plane
B= frequency plane

Need to Introduce Functional Descriptions as an Analysis Aid

Functional Block Diagram of White Light Holography



FUNCTIONAL OPTICAL BUILDING BLOCKS

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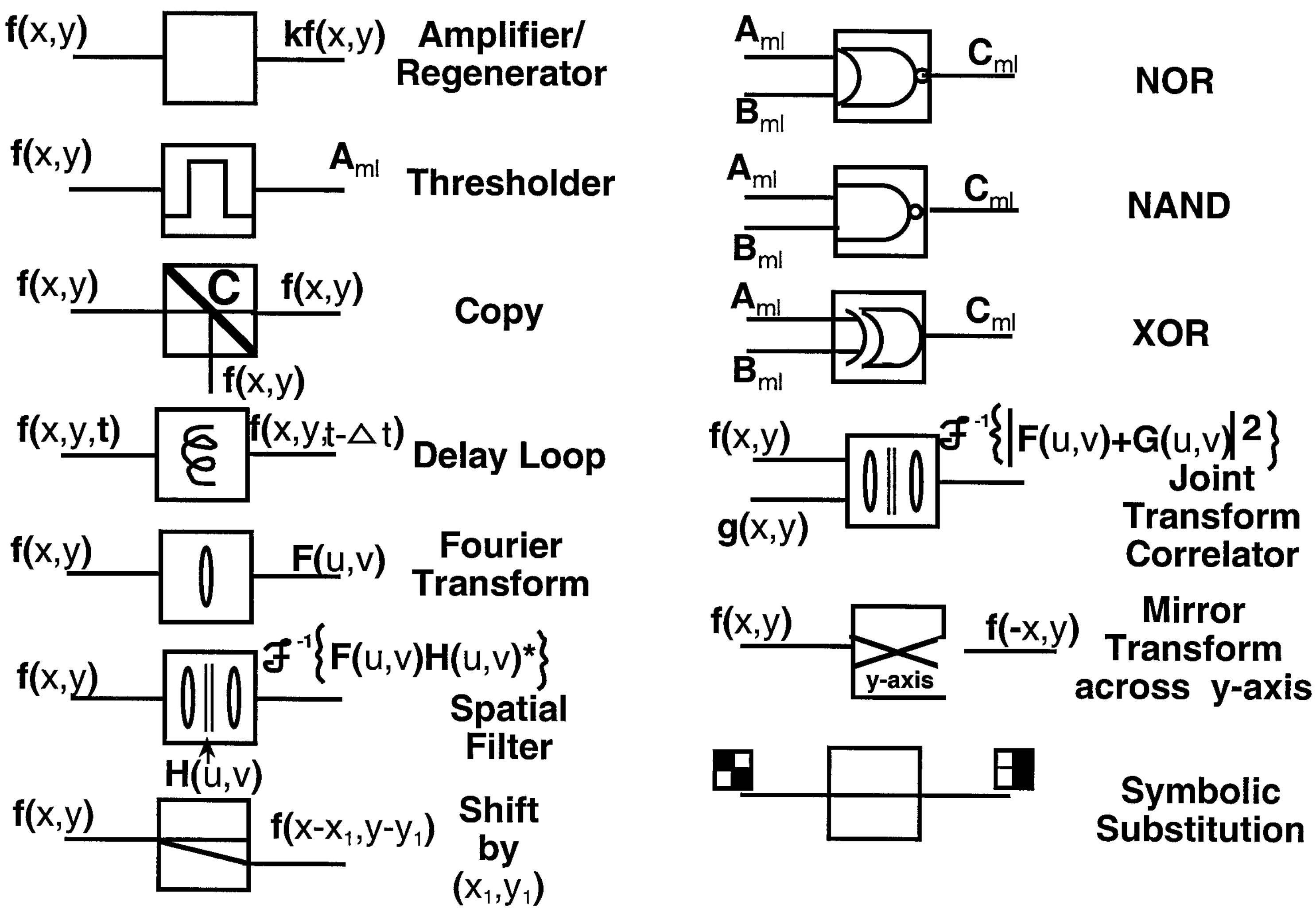

Key Realizations

- **Regeneration**
  - All optical regenerator/amplifier differs from electronic regenerator. Amplification adds noise so that infinite numbers of regeneration not possible.*
- **Timing control**
  - The ability to control the timing of the introduction of information into the processing loop possible; architecture may not be optimal for photons.
- **Logic Gates**
  - All optical realizations of these functions are bulky, power hungry, and difficult to integrate.

* J.H. Wilkinson, "Rounding Errors in algebraic Processes" (Prentice hall, Englewood Cliffs, N.J. 1963) Chapt. 1, pp 1-33.

Basic Requirements for Quantum Computing Implementation

DiVincenzo's determinations [2000]

1. Scalable physical system; i.e. 2^n dimensional complex vector from n-qubits
2. Ability to initialize qubits in simple fiducial state; e.g. |000…>
3. Decoherence time > gate operation time
4. Universal set of quantum gates
5. Qubit specific measurement capability

- Need to add some form of timing control.

Ref: arXiv:quant-ph/0002077 (April 2000)

Requirements for Quantum Communications

JPL

Communications applications

- Secret key distribution
- Multi party functions
  - » Appointment scheduling
  - » Secret sharing
  - » Game playing

DiVincenzo's determinations [2000]

6. Ability to interconvert stationary and flying qubits.
7. Ability to faithfully transmit flying qubits between specified locations.

Ref: arXiv:quant-ph/0002077 (April 2000)

Quantum Computing Building Blocks

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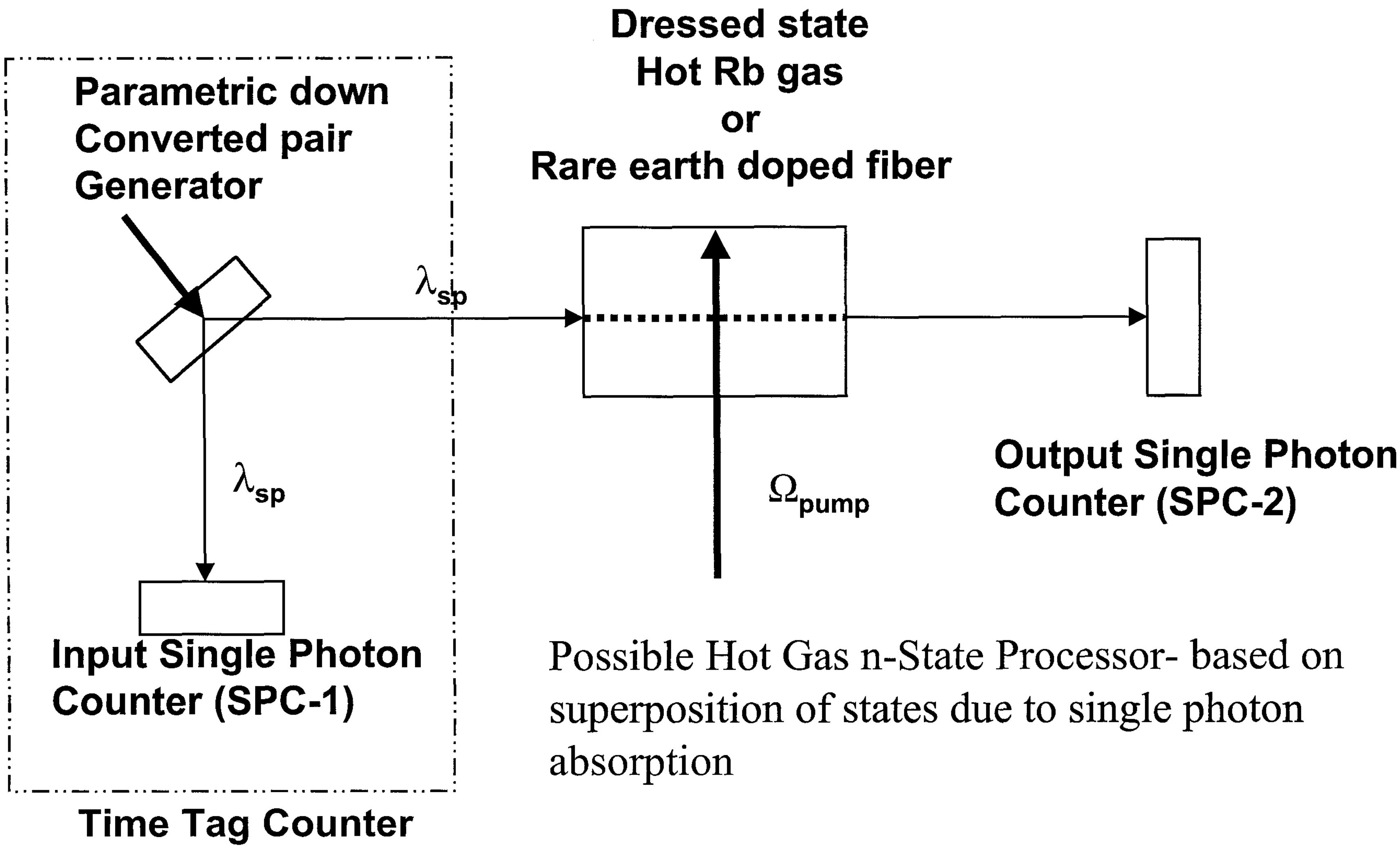
Devices

- Hyper parametric entangled photon generator
- Single photon detectors
- Quasi single photon generators
- MOTs
- Slow light atomic traps [SLATs] (BEC, atomic vapor, rare earth dopants)

Functions

- Hyper parametric single photon counters
- Slow light trap buffer storage

DiVincenzo's fifth requirement: Qubit specific measurement capability



Possible Hot Gas n-State Processor- based on superposition of states due to single photon absorption

What happens when one inputs a time ordered sequence of single photons?

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Legend
Atomic states
Input Photon States
Output Photon States

Dressed state
Hot Rb gas

$|n_1\rangle_1|n_2\rangle_2 \ldots |n_N\rangle_N$

r<<N

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4 \ldots |n_r\rangle_r$

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4 \ldots |n_r\rangle_r$

$|n_1\rangle_1|n_2\rangle_2|n_3\rangle_3|n_4\rangle_4 \ldots |n_r\rangle_r$??

Rb gas density	=	10^{11} cm^3,
cell length	=	4 cm
Beam waist?	=	0.1 cm
λ_{sp} = photon wavelength	=	800 nm
R = Laser rep rate	=	8 MHz
v_g = group velocity	=	1000 m/s
Λ = Photon spacing = v_g /R	=	125 μm (125 μs)

r = # entangled photons = λ_{sp}/Λ = 0.8

Does the output sequence maintain the same order?

Scaling up to n-entangled states?

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<u>Legend</u>
Atomic states
Input Photon States
Output Photon States
Entangled states

Dressed state
Hot Rb gas inside etalon

$|n_1\rangle_1|n_2\rangle_2\ldots|n_N\rangle_N$

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4\ldots|n_r\rangle_r$

$r \ll N$

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4\ldots|n_r\rangle_r \rightarrow |1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4\ldots|n_r\rangle_r \rightarrow |n_1\rangle_1|n_2\rangle_2|n_3\rangle_3|n_4\rangle_4\ldots|n_r\rangle_r$??

Rb gas density	=	10^{11} cm^3,
cell length	=	4 cm
Beam waist?	=	0.1 cm
λ_{sp} = photon wavelength	=	800 nm
R = Laser rep rate	=	8 GHz
v_g = group velocity	=	1000 m/s
Λ = Photon spacing = v_g /R	=	125 nm (125 ns)
r = # entangled photons	= λ_{sp}/Λ = 8	

CAN ONE DEFINE GATE FUNCTIONS

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What happens when one mixes the states through the application of microwave, electric, or magnetic fields?

Legend
Atomic states
Input Photon States
Output Photon States
Entangled states

Dressed state
Hot Rb gas

$|n_1\rangle_1|n_2\rangle_2\ldots\ |n_N\rangle_N$

r<N

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4\ldots\ |n_r\rangle_r$

$|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4\ldots\ |n_r\rangle_r$

$|n_1\rangle_1|n_2\rangle_2|n_3\rangle_3|n_4\rangle_4\ldots\ |n_r\rangle_r$??

How does one deal with the fact that we don't know an exact value for N?

Key Realizations

- Regeneration
  - Not a useful function for qubit operations.
- Timing control
  - The ability to control the timing of the introduction of information into the processing gate not well formulated.
- Logic Gates
  - Basic set of useful gates identified. Gate devices not yet realized.